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13. ABSTRACT *(Maximum 200 Words)*

The broad purpose of these experiments was to determine how the eye and head are normally coordinated, and to determine the optimal combination of eye and head movements for vision and reaching. The key findings were as follows:
(A) A head reticle disrupts eye position during head tracking, and is of little benefit for head tracking. (B) The head is moved to view targets only when such movements are unlikely to result in the individual missing subsequent targets. (C) Head movement improves hand/eye coordination, probably by increasing the likelihood that the subjects sees the target with both eyes. (D) A common eye movement monitor (scleral search coils) has a minor artifact that investigators should be aware of. (E) The eyeball is deformed when it is rotated through large angles. (F) Eye movements can be less accurate in the presence of flight simulator backgrounds. (G) Eye movement reaction times are slower for targets that can only be seen because of their colors. (H) When a target moves across a person's line of sight, the image of the target is smeared. This smear is reduced somewhat when the target is surrounded by other objects. (I) A person cannot voluntarily suppress eye movements directed opposite to a head movement, nor can they learn to suppress these eye movements.

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FINAL PERFORMANCE REPORT

GRANT NUMBER: AFOSR F49620-02-1-0050
The HEP Study: Head and Eye Pursuit Tracking Under Natural Conditions
PRINICIPAL INVESTIGATOR: Nicklaus Franklin Fogt, O.D., Ph.D.
GRANT PERIOD: November 15, 2001 – November 14, 2004
PROGRAM MANAGER: Dr. Willard Larkin

Objectives:

1. To compare eye and head tracking in the presence and absence of a structured background.

2. To understand the control of eye and head coordination in early tracking responses

3. To measure the propensity of human subjects to move the head.

4. To determine whether head movement is beneficial in hand/eye coordination tasks.

5. To measure the accuracy of fixation in extreme gaze.

6. To determine the influence of retinal smear on the visual discrimination of moving retinal images.

7. To understand the neural programming of two-dimensional catch-up saccades during ocular tracking.

8. To determine the influence of ocular tracking (eye tracking and head tracking) on prediction of the future position of a moving target.

Summary of Efforts:

Objective 1

We have determined that eye tracking is superior to head tracking, and that a reticle is disruptive to eye position during head tracking. Thus, we recommend that removal of the head reticle be considered in head tracking devices. We have also determined that a structured background can adversely effect eye tracking, but only when the target for tracking is very difficult to follow. Attention can therefore influence target tracking.

Objective 2

We found that unlike the eye, the head cannot be moved at the same velocity as a target unless a head position cue is provided.

Objective 3

We have found that head movement propensity declines as the location of a target to be fixated/acquired becomes more predictable.

Objective 4

We have found that head movement is beneficial for hand/eye coordination tasks. We are now in the process of determining why moving the head is beneficial. Thus far, we believe that subjects move the head to ensure binocularity, and that this most likely leads to better reaching performance.

Objective 5

We have found that fixation is accurate in extreme gaze, but that eye movement monitoring methods that infer the direction of gaze from the front of the eye may not be adequate.

Objective 6

We have determined that retinal smear is suppressed to some extent when an object is viewed in the presence of other proximal moving objects. However, the smear is not eliminated entirely by these proximal moving objects.

Objective 7

We are actively working on this issue. Preliminary results seem to show that horizontal and vertical catch-up saccades are either programmed together based on the two-dimensional trajectory of the target, or two-dimensional catch-up saccades are based on only one direction of target motion and the other direction of motion is programmed passively (i.e. not based on the motion of the target).

Objective 8

We are currently working on this area. Preliminary results show that predictions about the direction of objects derived from oculomotor sources is very short-lived.

Detailed Discussion of Efforts:

I. Head and eye pursuit tracking in the presence and absence of a structured visual field

The purpose of this portion of our studies is to compare the accuracy of head and eye tracking, and to determine whether a structured background influences the accuracy of eye tracking. Ocular tracking might be influenced by attention, or by

reflexive eye movements induced by a moving background. This has numerous basic and military implications.

Head steered weapons are now in service. For example, these devices are used in the United States Army AH-64 Apache Helicopter to aim machine guns, and on fixed-wing fighter jets to aim missile seekers. However, it remains unclear whether head tracking is appropriate for such tasks. One purpose of these studies is to compare head and eye tracking.

To address this issue, to date we have performed three studies of eye and head tracking. The first of these studies has culminated in a paper published in the October, 2002 issue of the journal Aviation, Space, and Environmental Medicine. This work formed a portion of Lt. Col. Nicholas Luthman's Masters thesis in Vision Science, which he completed in the Spring of 2001. Dr. Luthman was the program manager for the Laser Eye Protection Division of Brooks Air Force Base, and as far as I know he has now moved on to Germany to continue in the Laser Eye Protection Division.

In that study, we show that ocular fixation during head tracking is adversely affected when a visual cue to head position such as that currently available in head steered machines is provided. Ocular fixation was not, however, disrupted when the head was moved to track the target compared to when the head remained still. We also demonstrate that head tracking ability is adversely affected by this reticle. Our explanation for these results is that the visual cue to head position serves as a potent distractor and we argue that consideration should be given to removing this cue. We also speculate that the ocular pursuit system may overcome the compensatory vestibulo-ocular reflex by increasing the number of ocular saccades.

These experiments also have implications for the design of helmet mounted displays (HMDs). In immersed-environment displays, video imagery is used to represent the scene. The amount of high-resolution information or the amount of symbology presented in a helmet-mounted display may increase pilot workload and could cause decrements in tracking performance due to lack of attention. To explore this question, optometry/graduate student Nicky Lai and I performed several experiments on eye tracking in the presence of a structured visual background. We

have presented the results of these studies at the 2001 American Academy of Optometry Annual Meeting, the 2002 Association for Research in Vision and Ophthalmology Annual Meeting (for which Dr. Lai received a prestigious travel fellowship from the National Institutes of Health), and the 2002 American Academy of Optometry Annual Meeting. In 2005, this work culminated in a publication in the January issue of Aviation, Space, and Environmental Medicine.

The results of these studies can be summarized as follows. A flight simulator background has only a mild affect on the accuracy of ocular fixation when tracking a two-dimensional target containing relatively low frequencies. However, when the target is made more difficult to track by increasing the frequencies contained in the target, then the flight simulator background does have an adverse effect on tracking for all subjects. We believe that this is because fixation is lost more often with the difficult target, and therefore attention is diverted to the background during these periods of lost fixation. An incidental but interesting finding in this series of experiments is that subjects are able to "aim and shoot" the target quite accurately. That is to say, they are able to push a button when their eyes are on the target. Thus, they seem to be quite aware of the position of their eyes relative to the target. We are currently preparing a manuscript on Dr. Lai's Masters work. Dr. Lai graduated with the Masters of Vision Science in June, 2003. He recently completed a clinical residency at The Ohio State University College of Optometry and he is now on the clinical faculty at the College of Optometry.

In the coming year, we plan to continue these studies in the following ways. First, it is known that in operating static flight simulators or in actual field operations, a visually driven reflex called the opto-kinetic cervical reflex (OKCR) occurs. In the OKCR, pilots tilt the head toward the horizon during visual flight maneuvers where the aircraft is in roll. We will study this reflex using flight simulator software written for us by SDS International. I have adapted the software to allow synchronized recordings of head position, eye position, and plane orientation and position. Supplemental monetary support for this project has been supplied by the Naval

Aerospace Medical Research Laboratory, and collaborative support has been gained from Dr. Jennie Gallimore at Wright State University in Dayton, Ohio.

Our interest is in the relationship between the OKCR and eye movements. The current theory holds that the OKCR is executed in an attempt to maintain a stable horizon. However, this requires that the eyes be moved in the same direction as the head, which is often not the case. We will also use this software to study the influence of a radial flow field.

The second way we will continue these studies is to determine which elements of a structured background affect initiation of saccadic eye movements such as those involved in tracking. We will continue to study saccade initiation to saccade targets of different colors. Graduate student PremNandhini Satgunam, whose Masters work was funded by AFOSR through the grant described in this report, has studied this issue quite extensively. She recently presented her work at the ARVO 2004 meeting and at the American Academy of Optometry 2004 meeting. In December 2004, PremNandhini and I submitted a paper to the journal Vision Research on this work.

This work demonstrated that saccadic latencies were longer for chromatic targets than for achromatic targets when the contrasts of these two targets were matched. In the latter case, we will match the luminance of the colored targets, as well as the contrast between the targets and the background. Interesting developments to come out of this paper were methods to perform heterochromatic flicker photometry on a computer monitor, and methods to match the chromatic contrast of color targets to the luminance contrast of achromatic targets.

II. <u>Head and eye coordination during initiation of eye and head tracking responses</u>

When the head and eye are moved together in looking and tapping exercises, it has traditionally been argued that the head moves after the eye because of the large inertia of the head. Thus, although the eye and head seem to receive a common signal for combined movements, the eye moves before the head. There is reason to believe that the head can be moved prior to the eye, and that the inertial load of the head may

be overcome more easily than originally thought. One way to examine this question is to ask the subject to move the head toward a target.

We chose a moving target for two reasons. First, almost nothing is known about the coordination of the eye and head during unrestrained tracking responses to pursuit targets. To date, there have only a few studies on this topic and all have utilized monkeys as subjects. Second, acquisition with a head mounted tracking device is likely to involve moving targets. Thus far, we have discovered the following. First, when the moving target is peripheral to the head, the head moves in the direction of the target but at a velocity well beyond that of the target. Second, when the target is straight ahead, the head again moves at a velocity much greater than that of the target. This is clearly a problem for the operation of head aimed machinery. Graduate student Huan Sheng and I presented these results at the 2002 American Academy of Optometry Annual Meeting.

We have now completed the second phase of these studies, and we presented our results at the 2003 Association for Research in Vision and Ophthalmology Annual Meeting. We found that while the head cannot be used to track a target without a cue to head position, with a cue to head position the head is quite accurate in pursuing a target. This implies that while the head can be controlled adequately for target pursuit, individuals are not consciously aware of the location of the head.

III. <u>The effect of head movement on eye/hand/head coordination</u>

The impetus for this study comes from a widely held belief that moving the head results in poor eye/hand coordination. We initially presented findings on this topic at the 2001 American Academy of Optometry Annual Meeting, and we then presented them in a paper (2002) that was published in Optometry: The Journal of the American Optometric Association. We demonstrate that head movement can improve the accuracy of eye/hand movements executed in a rapid and repetitive fashion. Our speculation is that eye position information used in pointing is only accurate over a limited range of eye rotations (±15 degrees). Those data shown in our manuscript

seems to lend credence to this hypothesis, as turning the head only improved eye/hand coordination at target eccentricities greater than about 15 degrees.

We have continued these studies in several ways. First, we are working to determine when and why the head aids eye/hand coordination. We are currently working on a manuscript in which we are showing that in pointing at a target, when the head stops moving the vergence posture of the eyes is very accurate. This implies that the head is being rotated to attain a more accurate vergence posture. We have presented some of these data at the American Academy of Optometry annual meeting (2003).

Second, we are studying what motivates individuals to move the head. In one study, presented at the 2003 Association for Research in Vision and Ophthalmology Annual Meeting, we showed that when a target is made very predictable (target location >30 degrees eccentricity), head movements toward it nearly cease and the person instead moves only the eye to view the target. This directly contradicted a study on eye and head coordination in monkeys, where it was argued that the head is moved so as to keep the eye at a gaze angle less than 15 degrees.

In summary, what we are doing in these experiments is determining whether head movement helps one to track objects, to visually acquire objects, and to reach for objects. We are also determining how and when people move the head. Finally, we will determine whether people typically make optimal use of head movements.

IV. Measurement of eye position in extreme gaze

It has been argued that eye tracking (or head and eye tracking) may be more appropriate than head tracking alone for aiming weapons. However, the ability to monitor eye movements has so far been limited by technical considerations. In this study, published in August 2004 in the journal Optometry and Vision Science, we examined the accuracy of extreme gaze ocular fixation using scleral search coils. Scleral search coils are probably have the highest spatial and temporal resolution of any eye tracking system. We found that search coils slip on the eye at large angles of

gaze. We also found that monitoring eye position from the front of the eye is inadequate for indicating the direction of the fovea in extreme gaze. This is an important finding, as many eye movement devices presume that the front of the eye adequately indicates the direction the eye is viewing. This work was a collaborative effort between Dr. Tyson Brunstetter at the Naval Air Systems Command, Patuxent River, MD and myself.

V. Retinal smear and the influence of surrounding objects

The purpose of these experiments is to determine what influence retinal smear has on visual discrimination of moving objects. We have assessed this by comparing visual discrimination of single and surrounded moving targets. The initial work on this topic was presented at the 2004 ARVO meeting (for which graduate student Troy Bornhorst received a prestigious travel fellowship), and the work has culminated in a second poster to be presented at the Vision Sciences Society 2005 meeting and a recently submitted journal manuscript.

The results demonstrate that retinal smear does influence the visual discrimination of moving objects, but that this smear is attenuated in the presence of surrounding objects. This work has strong implications for models of motion deblurring.

VI. Two-dimensional trajectories of catch-up saccades

Current models of saccade generation suggest that the horizontal and vertical components of two-dimensional saccades are generated by separated neural controllers and later combined. However, catch-up saccades provide a unique model to test this hypothesis, because in order to generate accurate two-dimensional saccades both the horizontal and vertical retinal position errors must be evaluated. So far, these data suggest that the horizontal and vertical components of two-dimensional saccades are programmed simultaneously. We are currently developing software to analyze these data more quickly and efficiently.

VII. Oculomotor signals for predicting the future position of moving objects

We recently started this line of research. Preliminary results are to be presented at the Vision Sciences Society 2005 annual meeting. Thus far, we have found that prediction can be used to drive eye movements when a moving target is transiently occluded, but that this prediction is short lived.

Personnel Supported/List of graduate students in Vision Science and associated projects

A. Current Graduate Students

1. Premnandhini Satgunam (Ph.D. Candidate)
   A. Head and eye movements in a rapid, repetitive task
   B. Effects of color on saccadic eye movement latencies

   Ms. Satgunam's Master of Science project was funded through this grant
2. Toole, Andrew (Ph.D. Candidate) – currently supported as a research fellow by NIH T32 Grant
   A. Vergence eye movements with pulse disparities
   B. Two-dimensional catch-up saccade trajectories
3. Brett Garee (Master of Science Candidate)
   A. Head movement trajectory with step-ramp pursuit targets
   B. Calculations of binocular time during the alternate cover test

   Scheduled to graduate with Master of Science in Vision Science, June, 2005
4. James Miller (Master of Science Candidate)
   A. The influence of head and eye movement on prediction of future positions of pursuit target

   Scheduled to graduate with Master of Science in Vision Science, June, 2006

Students who have completed graduate studies

1. PremNandhini Satgunam, B.S., M.S. – see above
2. Troy Bornhorst, O.D., M.S.

A. Visual discrimination of moving stimuli

Graduated with Master of Science in Vision Science, June, 2004 and is now in private optometric practice in Cleveland, Ohio

3. Anthony Fox, O.D., M.S.

   A. Factors that influence vestibulo-ocular reflex cancellation

   Graduated with Master of Science in Vision Science, June, 2004 and is now in private optometric practice in Zanesville, Ohio

4. Nicky Lai, O.D., M.S.

   A. Two-dimensional saccades

   Graduated with Master of Science in Vision Science, June, 2003 and is currently on the clinical faculty at the Ohio State University College of Optometry

List of completed Master of Science publications –available through The Ohio State University Libraries

1. Nicky Y. Lai, 2003, "Effects of a simulated background and attention on two-dimensional target tracking"

2. Troy D. Bornhorst, 2004, "The effect of retinal image motion on discrimination of single and surrounded letters"

3. Anthony E. Fox, 2004, "Training the cancellation of the vestibulo-ocular reflex"

4. PremNandhini Satgunam, 2004, "Saccadic latency to colored targets"

List of Published Abstracts During the Grant Period

1. Uhlig, R. and Fogt, N. (2001) The effect of head movement on the accuracy and speed of a pointing task, *Optometry and Vision Science, 78,* 101.

2. Lai, N.Y. and Fogt, N. (2001) The influence of a simulated background on ocular pursuit, *Optometry and Vision Science, 78,* 102.

3. Lai, N.Y. and Fogt, N. (2002) The effect of a flight simulator background on two-dimensional smooth pursuit, *ARVO abstract* #963.

4. Sheng, H. and Fogt, N. (2002) Conscious control of the temporal sequence of eye and head movements, *Optometry and Vision Science, 79,* 225.

5. Lai, N.Y. and Fogt, N. (2002) The ability to judge eye position while tracking a moving target, *Optometry and Vision Science, 79,* 224.

6. Satgunam, P. and Fogt, N. (2003) Orienting head movements during head-free pursuit, *ARVO abstract* #2132.

7. Garee, B.T. and Fogt, N. (2003) The effect of voluntarily increasing head movement during eye-head pursuit, *ARVO abstract* #2133.

8. Frasco, C., Kulp, M., Mitchell, G.L., and Fogt, N. (2003) Validity of eye movement tests, *Optometry and Vision Science, 80(supplement)*, 43.

9. Satgunam, P. and Fogt, N. (2003) The effect of head rotation on reaching accuracy, *Optometry and Vision Science, 80(supplement)*, 200.

10. Bornhorst, T.D. and Fogt, N. (2004) The effect of retinal image motion on discrimination of single and surrounded letters, *ARVO (Association for Research in Vision and Ophthalmology) abstract* #2536.

11. Fox, A.E. and Fogt, N. (2004) Improvement in vestibulo-ocular reflex cancellation with visual feedback does not transfer when feedback is removed, *ARVO (Association for Research in Vision and Ophthalmology) abstract* #2522.

12. Satgunam, P. and Fogt, N. (2004) The effect of target color on saccadic latency, *ARVO (Association for Research in Vision and Ophthalmology) abstract* #2514.

13. Subramanian, V. and Fogt, N. (2004) The relationship between disparity vergence detection limits and stereoscopic detection limits, *ARVO (Association for Research in Vision and Ophthalmology) abstract* #4321.

14. Satgunam, P. and Fogt, N. (2004) Saccadic latency for equivalent chromatic and achromatic targets, *Optometry and Vision Science, 81(supplement),* 291.

15. Satgunam, P., Chitkara, M., and Fogt, N. (2005) Ocular tracking of transiently occluded targets, Accepted for presentation at the *2005 Vision Sciences Society Annual Meeting.*

16. Fogt, N. and Bornhorst, T.D. (2005) The influence of retinal smear on discrimination of single and surrounded moving letters, Accepted for presentation at the *2005 Vision Sciences Society Annual Meeting.*

List of Published and Submitted Papers During the Grant Period

1. Fogt, N., and Luthman, N. (2002) Ocular Fixation During Eye and Head Tracking With and Without a Visual Cue to Head Position, *Aviation Space and Environmental Medicine*, 73, 1031-1037.

2. Fogt, N., Uhlig, R., Thach, D.P., and Liu, A. (2002) The Influence of Head Movement on the Accuracy of a Rapid Pointing Task, *Optometry: Journal of the American Optometric Association*, 73, 665-673.

3. Brunstetter, T., Mitchell, G.L., and Fogt, N. (2004) Magnetic Field Coil Measurements of the Accuracy of Extreme Gaze Ocular Fixation, *Optometry and Vision Science*, 81, 606-615.

4. Fogt, N., Lai, N. (2005) Fixational errors for two-dimensional tracking tasks with black and complex backgrounds, *Aviation Space and Environmental Medicine*, 76, 46-51.

5. Good, G.W., Fogt, N., and Daum, K. (2004) Dynamic Visual Fields of One-Eyed Observers, *Optometry: Journal of the American Optometric Association*, In Press.

6. Satgunam, P., Fogt, N. (2004) Saccadic latencies for achromatic and chromatic targets, Submitted to *Vision Research* in Dec. 2004. In review.

7. Fogt, N., Bornhorst, T.D., and Novak, J.J. (2005) Visual discrimination of moving single and surrounded letters, Submitted to *Optometry and Vision Science* in February 2005. In review.

Published Book Chapter

1. Fogt, N. (2003) Eye Movements and Accommodation, In: The Encyclopedia of Optical Engineering, (Johnson & Diggers, Eds.), Marcel-Dekker, Inc.

Interactions/Transitions

Collaborations

There are numerous collaborations to date. The first collaboration has been arranged between my laboratory and individuals at the Naval Aerospace Medical Research Laboratory (NAMRL) in Pensacola, Florida. The point of contact is Lt. Tyson Brunstetter (now at the Naval Air Systems Command, Patuxent, MD). This collaboration is intended to extend our current studies of head and eye movement with

a simulated background. The software has now been written to measure eye and head movements as individuals fly a pre-selected flight path in the simulator. We have now arranged to do this project with the help of Dr. Jennie Gallimore at Wright State University. Dr. Gallimore is in the Department of Biomedical, Industrial and Human Factors Engineering, and she is an expert on software flight simulations and head tracking.

The second collaboration is one I am developing with Dr. Paul Havig, a researcher at Wright Patterson Air Force Base Human Effectiveness Air Force Research Labs. We are developing projects to understand the influence of eye and head movements and ocular accommodation on the visibility of flight symbology in cockpit.

The third collaboration occurred when I participated in an American Institute of Biological Sciences program review of the Medical Countermeasures for Laser Eye Injury program at the US Army Medical Research Detachment Walter Reed Army Institute of Research, Brooks City-Base, San Antonio, Texas. I was on the panel for this two day review of the program.

<u>Transitions</u>

First, I am setting up a magnetic field coil system at Wright Patterson with Dr. Havig (mentioned above) that will allow for head tracking at high sampling rates. We will use this system to measure the effects of head tracking recording delays when using head trackers in the cockpit.

Second, I am developing methodology to measure binocular accommodation with Dr. Havig. He is interested in measuring binocular accommodation with night vision goggles. I intend to help him design and perform this experiment.

The final transition is an encyclopedia chapter I wrote for the Encyclopedia of Optical Engineering. The Encyclopedia of Optical Engineering contains numerous chapters on issues related to the military such as night vision goggle optics, helmet-mounted display optics, and human factor issues such as those dealt with in my chapter. My chapter, entitled "Eye Movements and Accommodation", contains several

pieces of information on eye and head tracking derived from the research graduate student Nicholas Luthman and I performed over the past few years.

New discoveries, inventions, patent disclosures

A. New discoveries

1. A head reticle disrupts eye position during head tracking, which will influence the design of future head steered systems.
2. Head movement propensity is related to the predictability of a target.
3. Head movement is beneficial in eye/hand coordination tasks.
4. The head and eye are coordinated in reaching tasks so that the eyes attain binocularity
5. Scleral search coils slip on the eye in some people.
6. Instruments such as search coils that measure fixation position from the front of the eye may be inaccurate, because the eye is deformed at extreme angles of gaze.
7. Ocular saccades are relatively resistant to attentional distractors, except in extreme circumstances when target fixation is often lost.
8. Saccadic latencies are not influenced by the color of a target. However, saccadic latencies to chromatic targets are longer than those to achromatic targets. This indicates that the neural pathway that carries chromatic information is sluggish.
9. Retinal smear influences visual discrimination of a moving target, but the influence of retinal smear is attenuated when moving targets are surrounded by other characters.
10. Cancellation of the vestibulo-ocular reflex during eye-head target tracking cannot be voluntarily initiated, and it cannot be improved through practice.
11. Fusional vergence limits and stereoscopic limits match closely, indicating common controllers for motor and sensory systems.

B. New developments

1. Developed hardware and software to synchronize oculomotor and head movement recordings.
2. Developed hardware and software to synchronize oculomotor and head movement recordings with a flight simulator.
3. Developed technique to match the achromatic and chromatic contrasts of luminance and color targets.
4. Developed methodology to present moving retinal stimuli for brief periods so as to induce controlled retinal image motion.
5. Developed methodology to utilize the scleral search coil to measure the accuracy of extreme gaze ocular fixation.

Honors and Awards

1. 2002 - Naval Aerospace Medical Research Laboratory Contract - $30,000.00: for *Eye Movements and the Optokinetic Cervico-Ocular Reflex*
2. 2003 - The Ohio State University Alumni Award for Distinguished Teaching This is the highest award for teaching given at The Ohio State University
3. 2004 – FY2004 Defense University Research Instrumentation Program (DURIP) Award - $85,600.00:
   for *Measurements of eye, head, and hand movements under vibration in experienced and inexperienced subjects*

Grant applications submitted

1. June 2004 – Air Force Office of Scientific Research – Grant renewal submitted for The HEP Study: Head and eye pursuit tracking under natural conditions: $509,348.00
2. August 2004 – Defense University Research Instrumentation Program (DURIP) - Grant application submitted for The effect of unexpected head movements on eye tracking, head tracking, and hand coordination: $109,800.00